Answer to Essential Question 29.2: Solving for the mass converted to energy within the Sun every second gives $m = E/c^2 = \left(4\times10^{23}\ \text{J}\right)/\left(9\times10^{16}\ \text{m}^2/\text{s}^2\right) \approx 4\times10^{6}\ \text{kg}$. This is a huge mass, but it represents a tiny fraction of the Sun's mass of 2.0×10^{30} kg.

29-3 Radioactive Decay Processes

In general, there are three types of radioactive decay processes, named after the first three letters of the Greek alphabet, alpha, beta, and gamma. In the alpha and beta decay processes, a nucleus emits a particle, or a collection of particles, turning into a nucleus of a different element. The gamma decay process is more analogous to what happens in an atom when an electron drops from a higher energy level to a lower energy level, emitting a photon. Gamma decay occurs when a nucleus makes a transition from a higher energy level to a lower energy level, emitting a photon in the process. Because nuclear energy levels are generally orders of magnitude farther apart than are electron energy levels, however, the photon released in a gamma decay process is very high energy, and falls in the gamma ray region of the electromagnetic spectrum.

Radioactive decays can happen spontaneously when the products resulting from the decay process are more stable than the original atom or nucleus. In any kind of radioactive decay process, a number of conservation laws are satisfied, as explained in the box below.

All nuclear reactions and decays satisfy a few different conservation laws. First of all, the process can generally be viewed as a super-elastic collision, and thus linear momentum is conserved. Kinetic energy is generally not conserved, but any excess or missing kinetic energy can be explained in terms of a conversion of mass into kinetic energy. Charge must also be conserved in a reaction or a decay. In addition to the preceding guidelines, the number of nucleons (the number of protons plus neutrons) must also be conserved, a law known as conservation of nucleon number.

Alpha decay

An alpha particle is a helium nucleus, two protons and two neutrons, which is particularly stable. Heavy nuclei can often become more stable by emitting an alpha particle – this process is known as **alpha decay**. Equation 29.3 describes alpha decay, in which a nucleus with a generic chemical symbol X_1, with atomic mass number *A* and atomic number *Z*, transforms into a second nucleus, X_2, with an atomic number of *A*–4 and atomic number *Z*–2. The number of neutrons, protons, and electrons (assuming all three atoms are neutral) is the same on both sides of the equation.

$${}^{A}_{Z}X_1 \Rightarrow {}^{A-4}_{Z-2}X_2 + {}^{4}_{2}\text{He}.$$ (Equation 29.3: **General equation for alpha decay**)

A particular example of alpha decay is the transformation of uranium-238 into thorium-234.

$${}^{238}_{92}\text{U} \Rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}.$$ (Equation 29.4: **An alpha decay example**)

Table 29.3 in Section 29-8 gives the masses of a number of isotopes. The atomic masses of uranium-238, thorium-234, and helium-4 are 238.050786 u, 234.043596 u, and 4.002603 u, respectively. The total mass on the right side of Equation 29.4 is 238.046199 u, which is lower in mass, by 0.004587 u, than the mass of the uranium-238. How do we explain this mass difference?

The missing mass is converted to kinetic energy, which is shared by the two atoms after the decay. Using our conversion factor of 931 MeV/u, 0.004587 u corresponds to 4.273 MeV of kinetic energy, most of which is carried away by the helium nucleus after the decay.

Beta-minus decay

There are two kinds of beta decay, beta-plus and beta-minus. A beta-minus particle is familiar to us – it is an electron – so let's examine beta-minus decay first. The general equation for beta-minus decay, which takes the nucleus one step up the periodic table, is

$${}^{A}_{Z}X_1 \Rightarrow {}^{A}_{Z+1}X_2^{+} + {}^{0}_{-1}\mathrm{e}^{-} + \bar{\nu}_e. \qquad \text{(Eq. 29.5: \textbf{General equation for beta-minus decay})}$$

The beta-minus decay process can be viewed as one of the neutrons in the nucleus decaying into a proton and an electron (the electron is symbolized by ${}^{0}_{-1}\mathrm{e}^{-}$). The last term on the right-hand side of Equation 29.5 represents an electron anti-neutrino. In the early 20th-century, analysis of beta-minus decay processes seemed to indicate a violation of energy conservation and of momentum conservation. In 1930, Wolfgang Pauli proposed that the missing energy and momentum was being carried away by a particle that was very hard to detect, which Enrico Fermi called the **neutrino** (little neutral one). Pauli was proven correct, and we now know that the Sun emits plenty of neutrinos, which interact so rarely that the majority of neutrinos incident on the Earth pass right through without interacting at all! Note that, when comparing the masses on the two sides of the decay, you can neglect the mass of the anti-neutrino, and looking up the mass of the neutral version of the nucleus on the right accounts for the electron, because the atom on the right is positively charged.

An example of beta-minus decay is the decay of thorium-234 into protactinium-234.

$${}^{234}_{90}\mathrm{Th} \Rightarrow {}^{234}_{91}\mathrm{Pa}^{+} + {}^{0}_{-1}\mathrm{e}^{-} + \bar{\nu}_e. \qquad \text{(Eq. 29.6: \textbf{A specific example of beta-minus decay})}$$

Beta-plus decay

A beta-plus particle is a positron, which is the antimatter version of the electron. It has the same mass and the same magnitude charge as the electron, but the sign of its charge is positive. A beta-plus decay takes the nucleus one step down the periodic table.

$${}^{A}_{Z}X_1 \Rightarrow {}^{A}_{Z-1}X_2^{-} + {}^{0}_{+1}\mathrm{e}^{+} + \nu_e. \qquad \text{(Eq. 29.7: \textbf{General equation for beta-plus decay})}$$

The neutrino in this case is an electron neutrino (there are two other kinds of neutrino, each with an antimatter version). In this case, when comparing the masses on the two sides of the decay, you can neglect the mass of the neutrino. In addition to the mass of the neutral version of the nucleus on the right, you need to add two electron masses, one for the extra electron (the atom is negatively charged) and one for the positron, which has the same mass as the electron.

An example of beta-plus decay is the decay of astatine-210 into polonium-210.

$${}^{210}_{85}\mathrm{As} \Rightarrow {}^{210}_{84}\mathrm{Po}^{-} + {}^{0}_{+1}\mathrm{e}^{+} + \nu_e. \qquad \text{(Eq. 29.8: \textbf{A specific example of beta-plus decay})}$$

Gamma decay

In gamma decay, the atom does not turn into anything different, as the nucleus simply decays from a higher-energy state to a lower-energy state. Using an asterisk to denote the higher state, the general equation for a gamma decay is

$${}^{A}_{Z}X_1^{*} \Rightarrow {}^{A}_{Z}X_1 + \gamma. \qquad \text{(Equation 29.9: \textbf{General equation for gamma decay})}$$

Related End-of-Chapter Exercises: 4 – 6, 23, 45.

Essential Question 29.3: If a carbon-13 atom (${}^{13}_{6}\mathrm{C}$) experienced alpha decay, what would it decay into? Use the atomic mass data in Table 29.3 in Section 29-8 to help you explain why carbon-13 will not spontaneously undergo alpha decay.

Answer to Essential Question 29.3: If carbon-13 experienced alpha decay, the process would be written ${}^{13}_{6}\mathrm{C} \Rightarrow {}^{9}_{4}\mathrm{Be} + {}^{4}_{2}\mathrm{He}$. There are 13 nucleons and 6 protons on both sides of the reaction. Looking up the relevant masses in Table 29.3, we find that the total mass after the reaction is larger than the mass of the carbon-13 atom. Spontaneous reactions occur when the total mass of the decay products is less than the mass of the initial atom – in that case, the missing mass shows up as the kinetic energy of the decay products. Thus, carbon-13 will not spontaneously exhibit alpha decay, because it does not make sense from the perspective of energy conservation.

EXPLORATION 29.3A – Beta-minus bookkeeping

Let's analyze the beta-minus process given above in some detail, so we can make sense of the statement about not having to add the mass of an electron when we do the bookkeeping necessary to determine the mass that is converted to kinetic energy. Here's the beta-minus process we are considering, the decay of thorium-234 into protactinium-234.

$${}^{234}_{90}\mathrm{Th} \Rightarrow {}^{234}_{91}\mathrm{Pa}^{+} + {}^{0}_{-1}\mathrm{e}^{-} + \bar{\nu}_e .$$ (Eq. 29.6: **A specific example of beta-minus decay**)

Step 1 – *How many neutrons, protons, and electrons are in the neutral thorium-234 atom?*
A neutral thorium-234 atom has 144 neutrons, 90 protons, and 90 electrons.

Step 2 – *Given that, in beta-minus decay, a neutron turns into a proton, an electron, and an anti-neutrino, how many neutrons, protons, and electrons should we expect to have to account for after the decay?*
Afterwards, we will have lost a neutron and gained one proton and one electron, so we have to account for 143 neutrons, 91 protons, and 91 electrons.

Step 3 – *What happens to the electron that is created in the decay process? How many electrons will the protactinium atom have after the decay?*
The electron produced in the decay has enough energy to be emitted from the atom (this is why radioactive materials are dangerous, because they are emitting energetic particles), so the protactinium has the same number of electrons, 90, that the thorium started with. This is why the protactinium is labeled with a + charge, because it has 91 protons and only 90 electrons.

Step 4 – *When we look up the mass of protactinium-234 in the table, how many electrons does it include?*
The table gives the mass of the neutral version of the atom, so it accounts for 91 electrons. That turns out to be exactly the number we need to account for, 90 electrons in the positively-charged protactinium, and 1 more emitted from the atom. So, looking up the mass of the neutral form of protactinium means we have already accounted for the mass of the electron that is emitted from the nucleus. Note that we don't need to worry about the mass of the anti-neutrino. Neutrinos and anti-neutrinos have such a small mass that we have yet to be able to determine the mass accurately.

Step 5 – *How much energy is emitted in this particular decay?*
Looking up the masses in the table, we get a mass for thorium-234 of 234.043596 u, while protactinium-234 has a mass of 234.043302 u. Subtracting the protactinium mass from the thorium mass gives a missing mass of 0.000294 u. Using the conversion factor 931.5 MeV/u, to convert to energy, gives us an energy of 274 keV. Almost all this energy is carried off in the form of kinetic energy by the electron and the anti-neutrino (the protactinium has a very small fraction of the kinetic energy).

EXPLORATION 29.3B – Beta-plus bookkeeping

Now, we will do a similar analysis of a beta-plus process, to see how we do the bookkeeping necessary to determine the mass that is converted to kinetic energy in that case. The specific beta-plus decay process we are considering is the decay of astatine-210 into polonium-210.

$${}^{210}_{85}\text{As} \Rightarrow {}^{210}_{84}\text{Po}^{-} + {}^{0}_{+1}\text{e}^{+} + \nu_e . \quad \text{(Eq. 29.8: \textbf{A specific example of beta-plus decay})}$$

Step 1 – ***How many neutrons, protons, and electrons are in the neutral astatine-210 atom?***
A neutral astatine-210 atom has 125 neutrons, 85 protons, and 85 electrons.

Step 2 – ***Given that, in beta-plus decay, a proton turns into a neutron, a positron, and a neutrino, how many neutrons, protons, electrons, and positrons should we expect to have to account for after the decay?***
Afterwards, we will have lost a proton and gained one neutron and one positron, so we have to account for 126 neutrons, 84 protons, 85 electrons, and one positron.

Step 3 – ***How many electrons will the polonium atom have after the decay?***
The decay has no impact on the number of electrons, so the polonium has the same number of electrons, 85, that the astatine started with. This is why the polonium is labeled with a negative charge, because it has 84 protons and 85 electrons.

Step 4 – ***When we look up the mass of polonium-210 in the table, how many electrons does it include? What else do we need to account for, in addition to the mass of polonium-210?***
The table gives the mass of the neutral version of the atom, so it accounts for 84 electrons. There is one additional electron to account for, as well as the positron. The positron, being the anti-matter equivalent of the electron, has the same mass as the electron, so we also need to add 2 electron masses (one for the extra electron, and one for the positron) to correctly account for all the mass there is after the decay. Once again, the neutrino has a negligible mass.

Step 5 – ***How much energy is emitted in this particular decay?***
Looking up the masses in the table, we get a mass for astatine-210 of 209.987148 u, while polonium-210 has a mass of 209.9828737 u. Adding in two electron masses (each with a mass of 0.00054858 u) brings the total mass of the products to 209.9839709 u. Subtracting the total mass afterwards from the astatine mass gives a missing mass of 0.003177 u. Using the conversion factor 931.5 MeV/u, to convert to energy, gives us an energy of 2.96 MeV. Again, almost all this energy is carried off in the form of kinetic energy by the positron and the neutrino.

Key idea: In a beta-minus decay, looking up the mass of the neutral version of the product atom accounts for the electron, because the atom on the right is positively charged. In a beta-plus decay, calculating the mass of the products correctly requires adding two electron masses, in addition to the neutral version of the product atom, to account for one electron and the positron.

Related End-of-Chapter Exercises: 20, 21.